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Fuel Cycle Research and Development

Advanced Fuels Campaign Overview

Jon Carmack

National Technical Director

Frank Goldner

Federal Project Manager

DOE-NEUP FY2014 Call Webinar

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INL/MIS-14-31997

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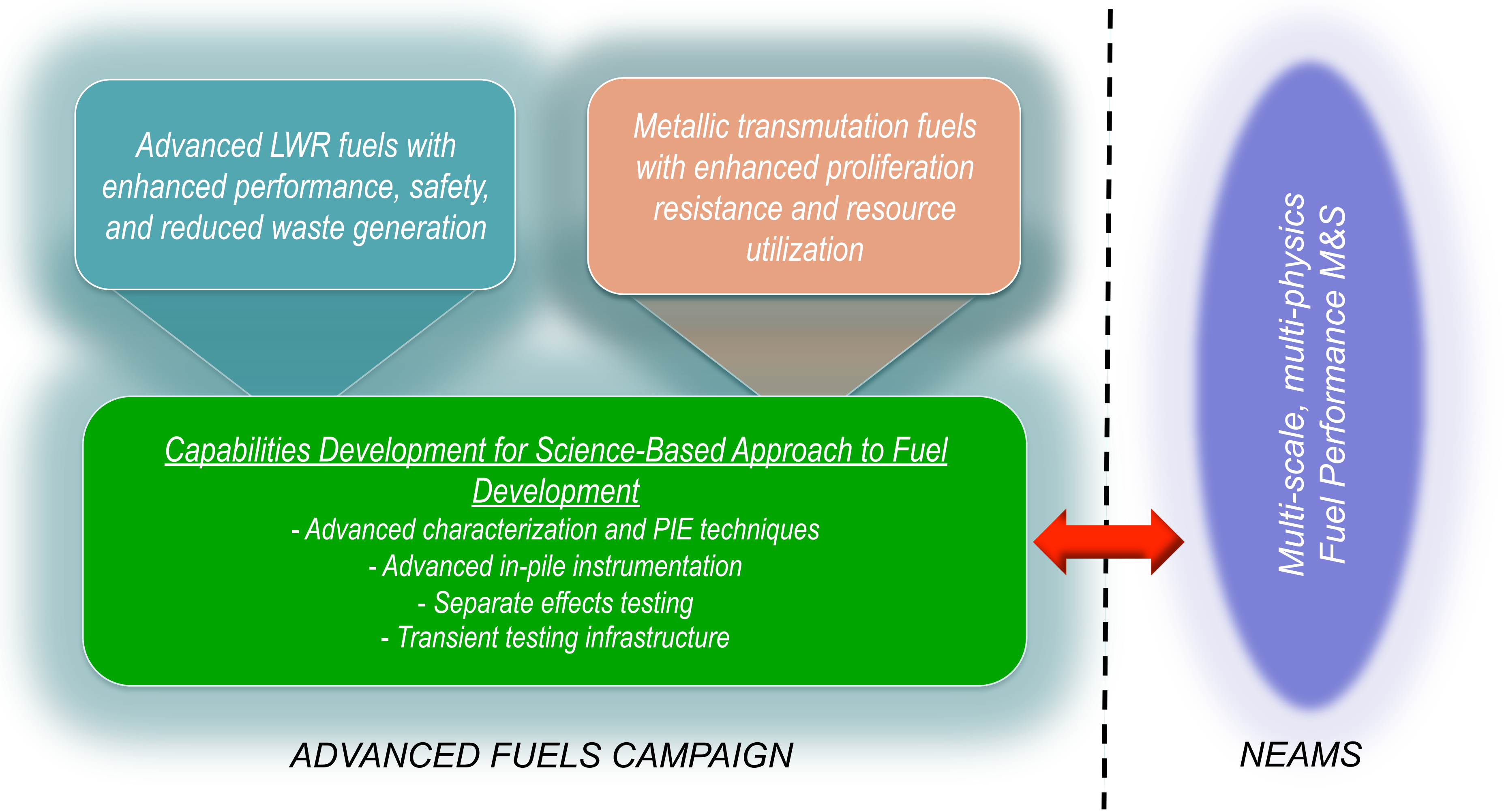
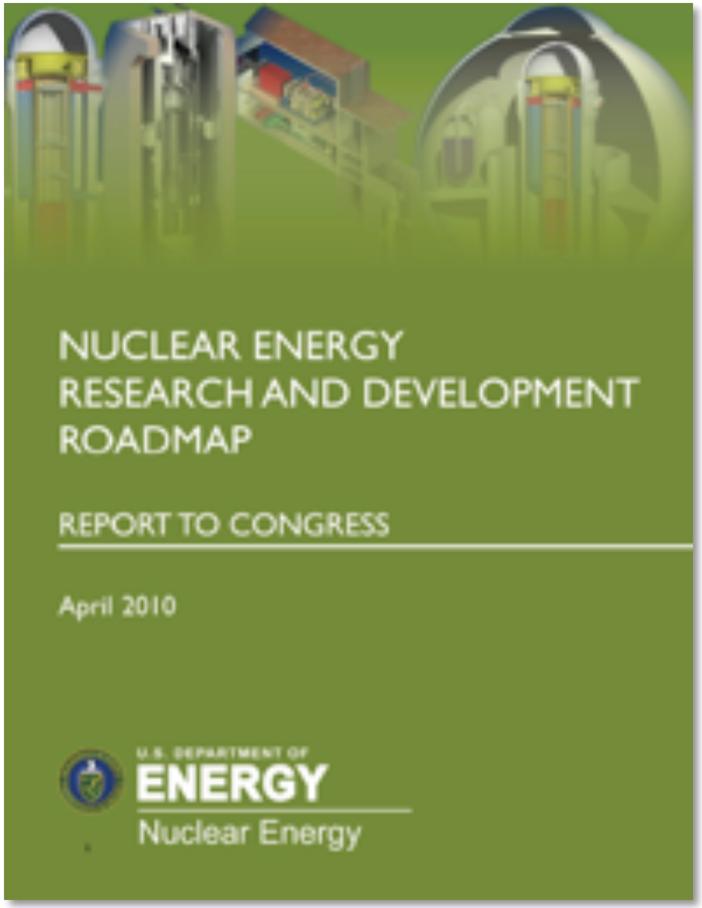
The FCRD Advanced Fuel Campaign is tasked with development of near term Accident Tolerant LWR fuel technology and performing research and development of long term resource enhancement options.



AFC High Level Technical Objectives (5-year)

- Identify and select advanced LWR fuel concepts for development towards lead test rod testing within the subsequent 5 to 7 years
- Complete the conceptual design for the baseline transmutation fuel technologies with emphasis on the fundamental understanding of the fuel fabrication and performance characteristics
- Identify and demonstrate feasibility of innovative concepts that provide considerable advantage compared to baseline technologies (Grand Challenge)
- Achieve state-of-the art R&D infrastructure that can be used to transition to “science-based” approach that can be used to accelerate further development of selected concepts
- Support the development of the predictive, multi-scale, multi-physics fuel performance code.



http://energy.gov/sites/prod/files/NuclearEnergy_Roadmap_Final.pdf

ATF for a LWR System Should Tolerate Loss of Active Cooling for A Significant Period of Time

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*Fuels with **enhanced accident tolerance** are those that, in comparison with the standard UO_2 – Zr system, can **tolerate loss of active cooling** in the core for a **considerably longer time period** (depending on the LWR system and accident scenario) while maintaining or improving the fuel performance during normal operations.*

Improved Reaction Kinetics with Steam and Slower H2 Generation
- Heat of oxidation
- Oxidation rate
- Hydrogen production
- Hydrogen embrittlement of the cladding

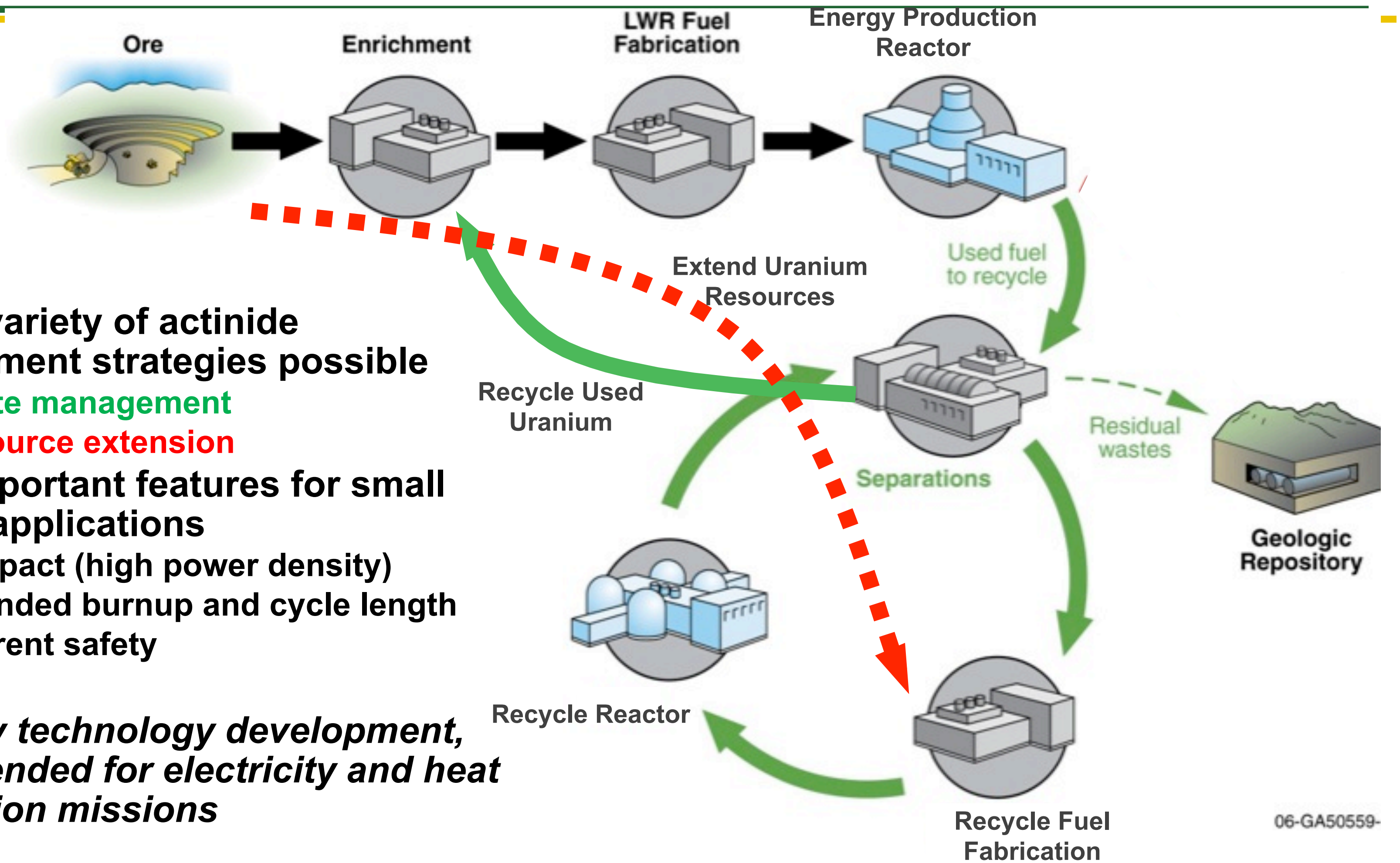
Improved Cladding Properties
- Clad fracture
- Geometric stability
- Thermal shock resistance
- Melting of the cladding

High temperature during loss of active cooling

Improved Fuel Properties
- Lower operating temperatures
- Clad internal oxidation
- Fuel relocation / dispersion
- Fuel melting

Enhanced Retention of Fission Products
- Gaseous fission products
- Solid/liquid fission products

Actinide Management in Fast Reactors



- **A wide variety of actinide management strategies possible**
  - **Waste management**
  - **Resource extension**
- **Also, important features for small reactor applications**
  - **Compact (high power density)**
  - **Extended burnup and cycle length**
  - **Inherent safety**
- ***With key technology development, also intended for electricity and heat production missions***

Near term goals for advanced and accident tolerant fuels for LWRs

- **Utilize infrastructure at laboratories to support fabrication, irradiation, and testing of accident tolerant concepts.**
- **Initiate irradiation in ATR of initial ATF concepts, additional concepts will follow.**
- **Initiate test planning and preliminary design of loop testing for ATF in the ATR, needed for cladding/coolant interaction.**
- **Begin preliminary design of TREAT transient loop for ATF.**
- **Industry FOAs and University IRPs. FOA's need 2nd allotment of funding in early 2015.**

Metallic Transmutation Fuel Technology Development

POC: Steve Hayes (INL) Technical Lead for Transmutation Fuel

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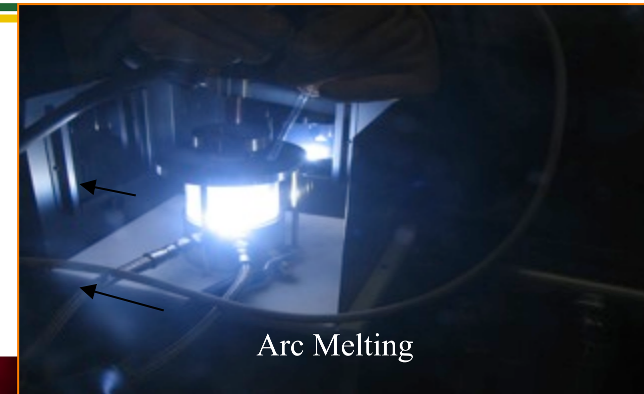
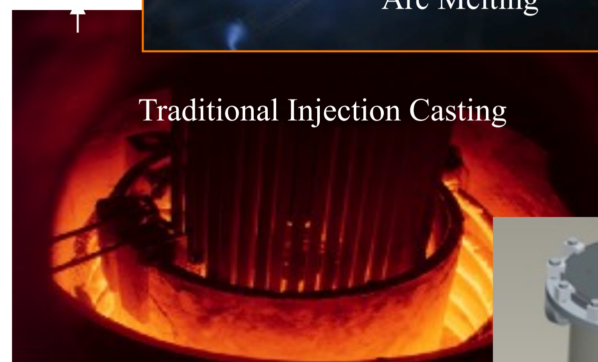
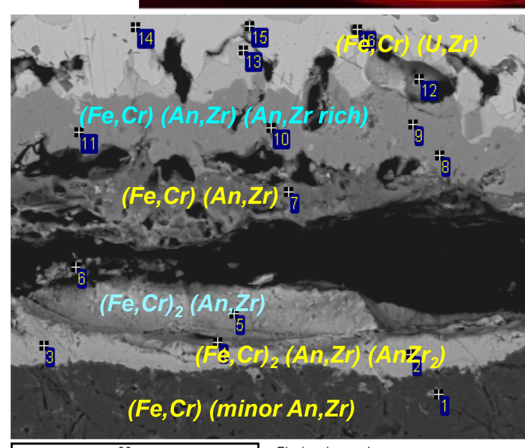
- **Conduct research and development supporting 2050 demonstration of full recycle at engineering scale.**
  - ***Advanced casting and fabrication techniques***
  - ***Characterization of material properties of minor actinide bearing fuels.***
  - ***Irradiation behavior of minor actinide bearing fuel compositions***
  - ***Development of advanced claddings having high burnup capability.***







Cross Cutting Technology Development Activities

- **Initiate prototypic testing of advanced in-situ and advanced in-pile measurement techniques.**
- **Continue development of advanced characterization techniques including hot cell mockup of multi-sensor apparatus, IMCL population, and advanced PIE methods.**
- **Continue developing experiment modeling and simulation with capability Bison code. Expand use to Accident Tolerant Fuel concepts.**
- **Obtain Am and Np feedstock for use in the domestic programs as well as fulfilling US commitments to international agreements.**

FY2015 NEUP Fuel Cycle 2.1 and 2.2 Call

- **FC-2.1: Advanced Nuclear Fuel, Cladding, and Core Components**

Advanced fabrication techniques applicable to fuel and core related systems of interest to the Advanced Fuels Program, (ie, accident tolerant fuels for light water reactors and transmutation fuels for fast spectrum reactors). Novel fabrication techniques for fuels and core structural materials, having the potential for economic, material performance, or manufacturability improvements over existing fabrication techniques, are desired for the fuel systems currently under study by the Advanced Fuel Campaign.

- **FC-2.2: Advanced Characterization Techniques**

Advanced characterization techniques to enhance the ability to link integral experimental data with microstructural-level material property behavior are desired. Ideally, these experimental techniques will produce data to be used in the validation of material property and fuel performance models. The model should be consistent and compatible with the NEAMS MBM fuel performance tools.

Technologies NOT of interest in this call include; thorium based fuels and molten salt based technologies.

FY2015 FC-1 Integrated Research Project

- **Evaluation of Fuels and Systems with Enhanced Accident Tolerance (IRP-FC-1)**

- **Goal: Promote the development of advanced modeling tool(s) capable of simulating the behavior of a fuel system at the core level needed to assess the time to melting of the fuel and core components. Ideally, the computational tool(s) will, to as great an extent as reasonable, be built upon the advanced modeling and simulation tools under active development, and already at an advanced state, by DOE-NE's NEAMS program. In particular, development and coupling of appropriate behavior models and a consistent simulation strategy to effectively analyze the following key areas up to the point of melting:**
  - **Cladding and core component performance**
  - **Thermo-mechanical fuel performance**
  - **Steady-state and transient neutronics**
  - **Thermal hydraulics**

- **Most importantly, the tool(s) must be able to provide an estimate of the time to melt for core components.**
- **Strongly encourage the use of DOE-NE4 NEAMS Program Tools**

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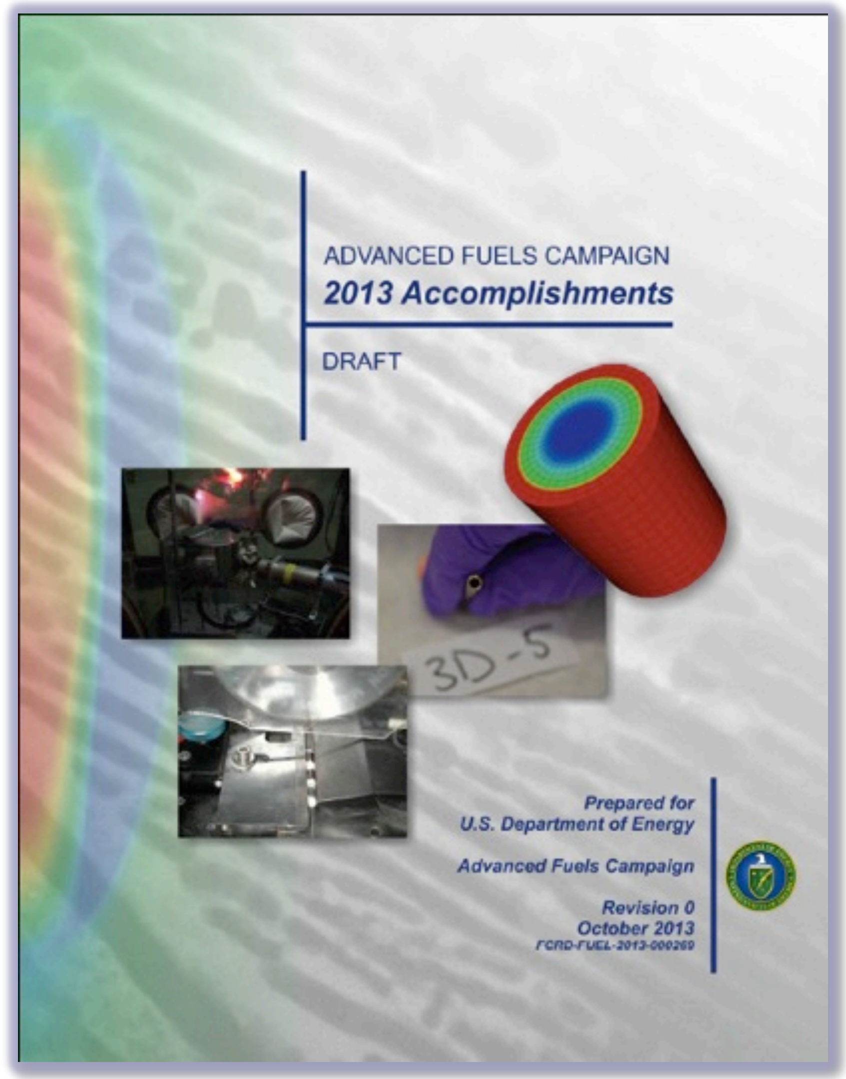
Recent Advanced Fuels Campaign Documents – Now Available

OSTI Document Links of Interest:

2013 Accomplishments Report
http://www.osti.gov/scitech/servlets/purl/1120800

Overview of Accident Tolerant Fuel Program
http://www.osti.gov/scitech/servlets/purl/1130553

Accident Tolerant Fuel Performance Metrics
http://www.osti.gov/scitech/servlets/purl/1129113



Contact Information

- **Federal Program Manager: Frank Goldner**
  - frank.goldner@nuclear.energy.gov

- **National Technical Director: Jon Carmack**
  - jon.carmack@inl.gov

- **Please review previous fuel related awards on www.neup.gov.**

Background

The Advanced Fuels Campaign is Directly Supported By a Large Part of the U.S. Nuclear Complex

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National Laboratories

INL Idaho National Laboratory

Oak Ridge National Laboratory

Brookhaven National Laboratory

Argonne National Laboratory

Los Alamos National Laboratory

Pacific Northwest National Laboratory

Universities

UF University of Florida — The Foundation for The Gator Nation

University of Illinois — Urbana-Champaign • Chicago • Springfield

UT The University of Tennessee — Knoxville, Chattanooga, Martin, Tullahoma, Memphis

MIT

Texas A&M University

Georgia Tech

W

M

Nuclear Industry

GE imagination at work

Westinghouse

AREVA

EnergySolutions — We're part of the solution

2009 – 2012 Funded NEUP Fuels Projects

Lead University	Title	PI
University of California Davis	Computational Design of Advanced Nuclear Fuels	Sergey Savrasov
University of Wisconsin-Madison	Ab Initio Enhanced Calphad Modeling of Actinide Rich Nuclear Fuels	Dane Morgan (Associate Professor)
Georgia University of Technology	Fundamental understanding of ambient and high temperature plasticity phenomena in structural materials in advanced reactors	Chaitanya Deo, Dave McDowell, Ting Zhu
University of Texas at Dallas	Simulations of Failure via Three-Dimensional Cracking in Fuel Cladding for Advanced Nuclear Fuels	Hongbing Lu
Dartmouth College	“Freeze-casting” as a Novel Manufacturing Process for Fast Reactor Fuels	Ulrike G.K. Wegst
University of Florida	Development of Innovative High Thermal Conductivity UO2 Ceramic Composite Fuel Pellets with Carbon Nano-Tubes Using Spark Plasma Sintering	Ghatu Subhash
Idaho State University	Fuel Performance Experiments on the Atomistic Level, Studying Through Engineered Single Crystal UO_2	Eric A. Burgett
University of California Santa Barbara	Optimized Compositional Design and Processing-Fabrication Paths for Larger Heats of Nanostructured Ferritic Alloys	G. R. Odette
Case Western Reserve University	Improved Accident Tolerance of Austenitic Stainless Steel Cladding through Colossal Supersaturation with Interstitial Solutes	Frank Ernst
Ohio State University	Testing of Sapphire Optical Fiber and Sensors in Intense Radiation Fields, when subjected to very high temperatures,	Thomas E. Blue
University of Tennesee	Better Radiation Response and Accident Tolerance of Nanostructured Ceramic Fuel Materials	Yanwen Zhang
University of Florida	Development of Innovative Accident Tolerant High Thermal Conductivity UO_2 –Diamond Composite Fuel Pellets	James Tulenko
University of Wisconsin-Madison	Development of Advanced High Uranium Density Fuels for Light Water Reactors	James Blanchard
University of Kentucky	Elastic/Inelastic Measurement Project	Steven W. Yates
Idaho State University	Nanovision	Eric A. Burgett
Univ of Notre Dame	Microscopic Fuel Particles produced by Self-Assembly of Actinide Nanoclusters on Carbon Nanomaterials	Chongzheng Na

New (6) 2013 Awarded University NEUP Grants (Currently expecting 8 new 2014 awards)

- **Developing Ultra-Small Scale Mechanical Testing Methods and Microstructural Investigation Procedures for Irradiated Materials**, University of California, Berkeley - Dr. Peter Hosemann
- **Multiphase Nanocrystalline Ceramic Concept for Nuclear Fuel**, University of California, Irvine - Dr. Martha L. Mecartney
- **Innovative Coating of Nanostructured Vanadium Carbide on the F/M Cladding Tube Inner Surface for Mitigating the Fuel Cladding Chemical Interactions,** University of Florida – Dr. Yong Yang
- **U_3Si_2 Fabrication and Testing for Implementation into the BISON Fuel Performance Code**, University of South Carolina – Dr. Travis Knight
- **Optical Fiber Based System for Multiple Thermophysical Properties for Glove Box, Hot Cell and In-Pile Applications**, Utah State University – Dr. Heng Ban
- **Correlating Thermal, Mechanical, and Electrical Coupling Based Multiphysics Behavior of Nuclear Materials Through In-Situ Measurements**, Purdue University – Dr. Vikas Tomar

DOE-NE funded FY12 IRPs on Accident Tolerance Fuel and Advanced Reactor Design

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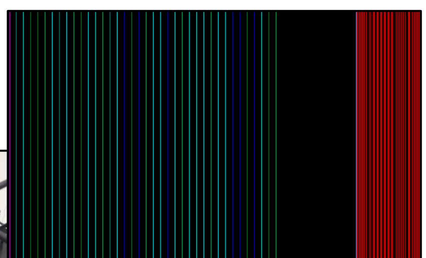
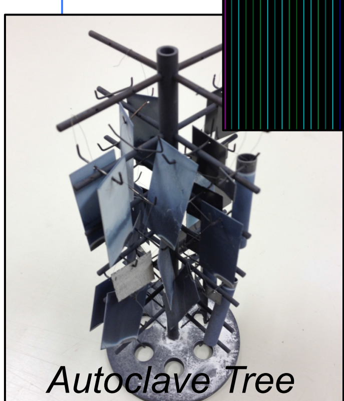
University of Tennessee

- Ceramic coatings for cladding: MAX phase and multi-layer ceramics
- Team: Penn State, U. Michigan, UC Boulder, LANL, Westinghouse, Oxford, U. Manchester, U. Sheffield, U. Huddersfield, ANSTO
- Approach:
  (i) MAX phase ceramic coatings and
  (ii) graded interface architecture (multilayer) ceramic coatings, using yttria-stabilized zirconia (YSZ) as the outer protective layer



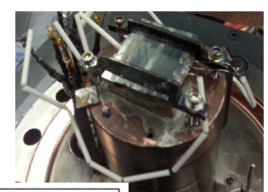


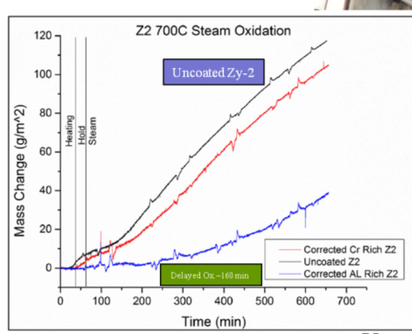
Autoclave Tree

THE UNIVERSITY of TENNESSEE
KNOXVILLE, CHATTANOOGA, MARTIN, TULLAHOMA, MEMPHIS

University of Illinois

- Engineered Zr alloy cladding
- Team: U. Michigan, U. Florida, INL, U. Manchester, ATI Wah Chang
- Approach:
  (i) application of a coating layer to Zr base or
  (ii) modification of the bulk Zr cladding composition to promote precipitation of minor phase(s) during fabrication





UNIVERSITY OF ILLINOIS
URBANA-CHAMPAIGN • CHICAGO • SPRINGFIELD

Georgia Institute of Technology

- *Engineered Zr alloy cladding*

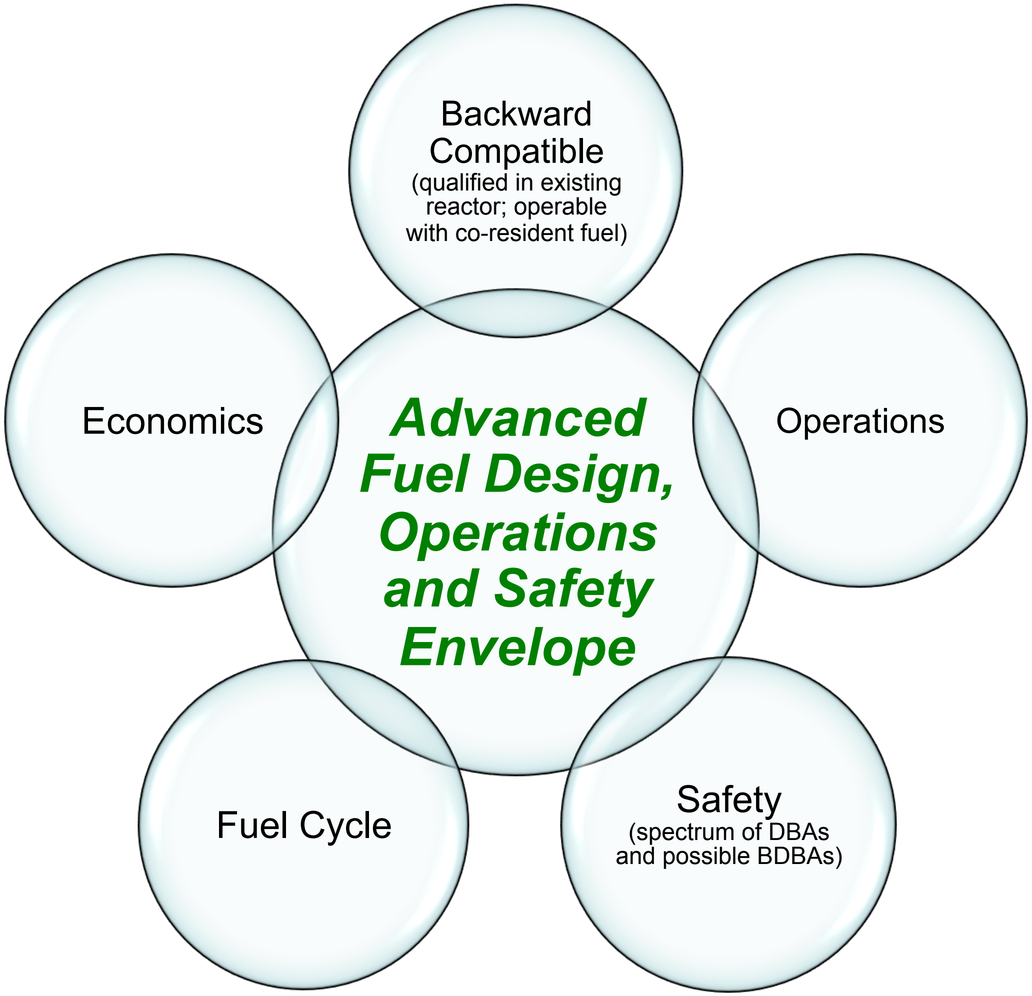
Team: U. Michigan, Virginia Tech, U. Tennessee, U. Idaho, Morehouse College, INL, Westinghouse Electric, Southern Nuclear, Polytechnic U. Milan, U. Cambridge

- Approach:

– Focus on design of advanced LWR concepts (beyond Gen III+) and associated fuel designs.
– Whole synergistic design (structures, components, materials including fuel and cladding, passive features, etc.) that would make the reactor inherently safe
– Improvements to all GEN IV performance goals including sustainability (fuel use/waste minimization), economics, proliferation resistance and physical protection

Georgia Tech

New ATF Designs Must Meet the LWR Operations, Safety and Fuel Cycle Constraints



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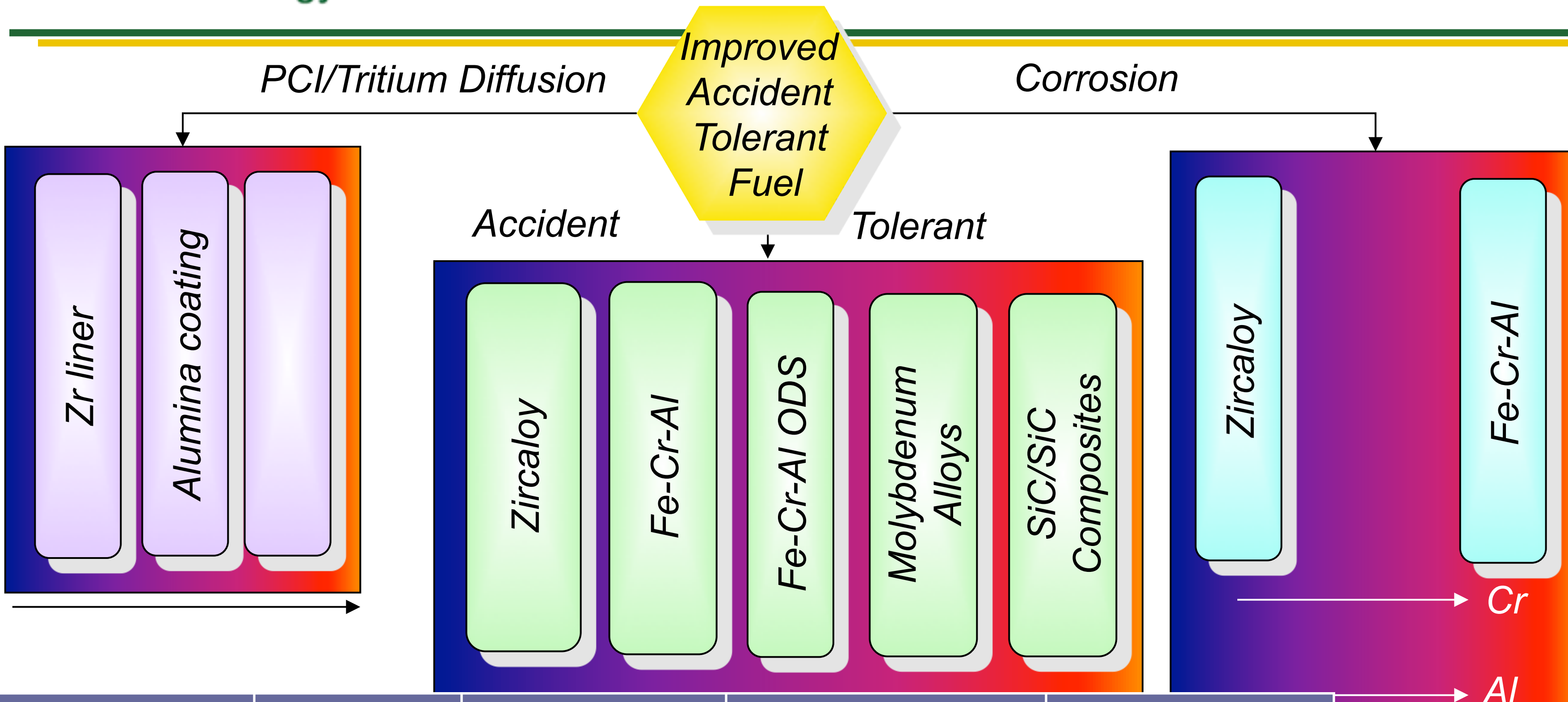
Development of Improved Accident Tolerant Cladding Materials

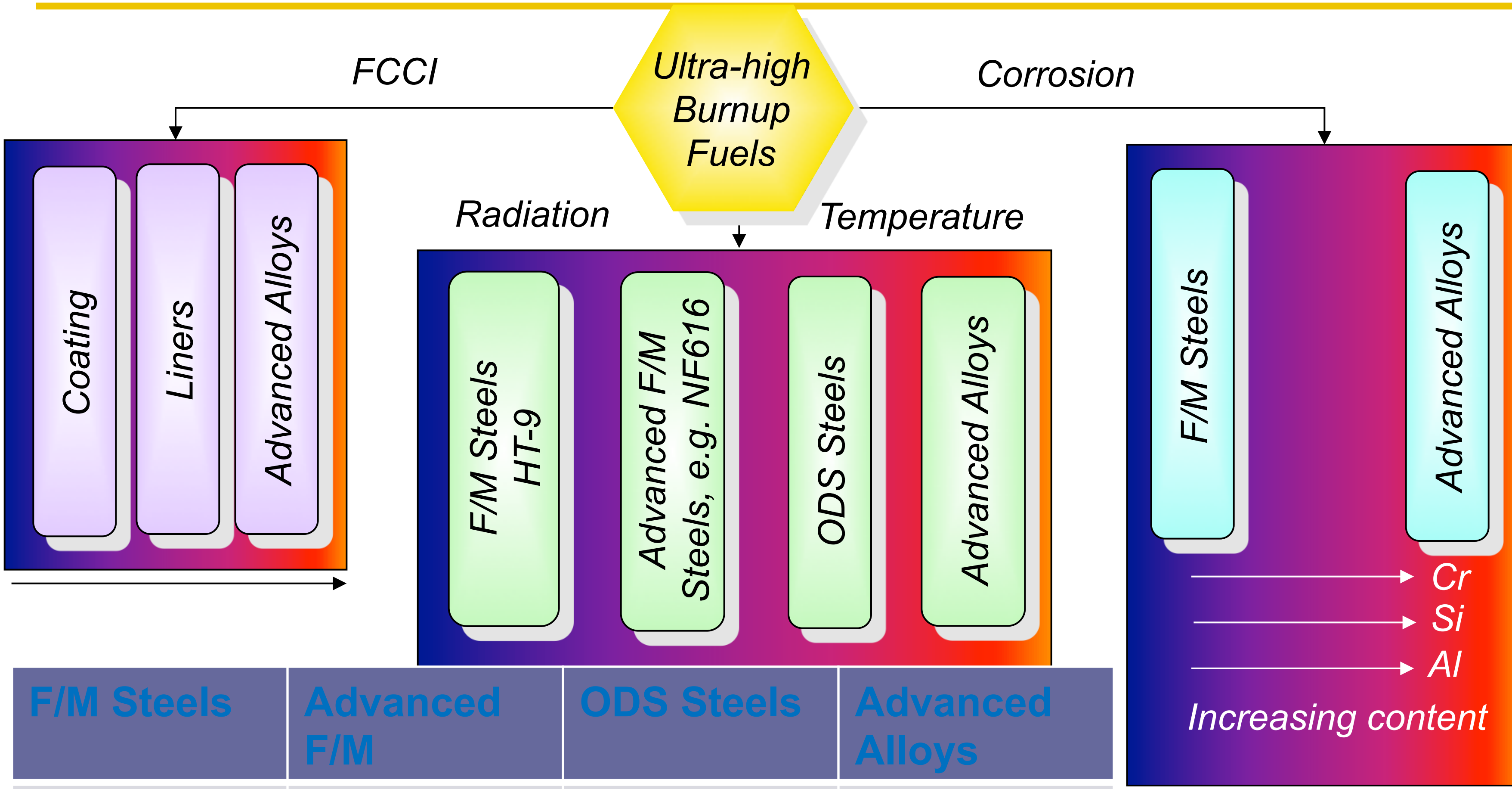
Lance Snead (ORNL) – Technical Lead for LWR Cladding



Zircaloy	Fe-Cr-Al	Fe-Cr-Al ODS	Molybdenum Alloys	SiC/SiC Composites
Zircaloy 2, Zircaloy 4, Zirlo, M5, Zr-1Nb	APM, APMT Kanthal (family)	MA-956, PM2000	Low carbon arc cast (LCAC) Mo, Mo-La, Mo-Re, TZM CVD-Mo	Nuclear Grade (Type-S Nicalon or Tyranno SA fibers CVI SiC or NITE matrix)

Enabling a Multi-fold Increase in Fuel Burnup over the Currently Known Technologies

POC: Stuart Maloy (LANL) Technical Lead for Transmutation Fuel Cladding



F/M Steels	Advanced F/M	ODS Steels	Advanced Alloys
HT-9, T91	NF616 (T92), Eurofer 97, F82H	MA957, 14YWT, 9YWTV	Metallic glasses, Titanium aluminides

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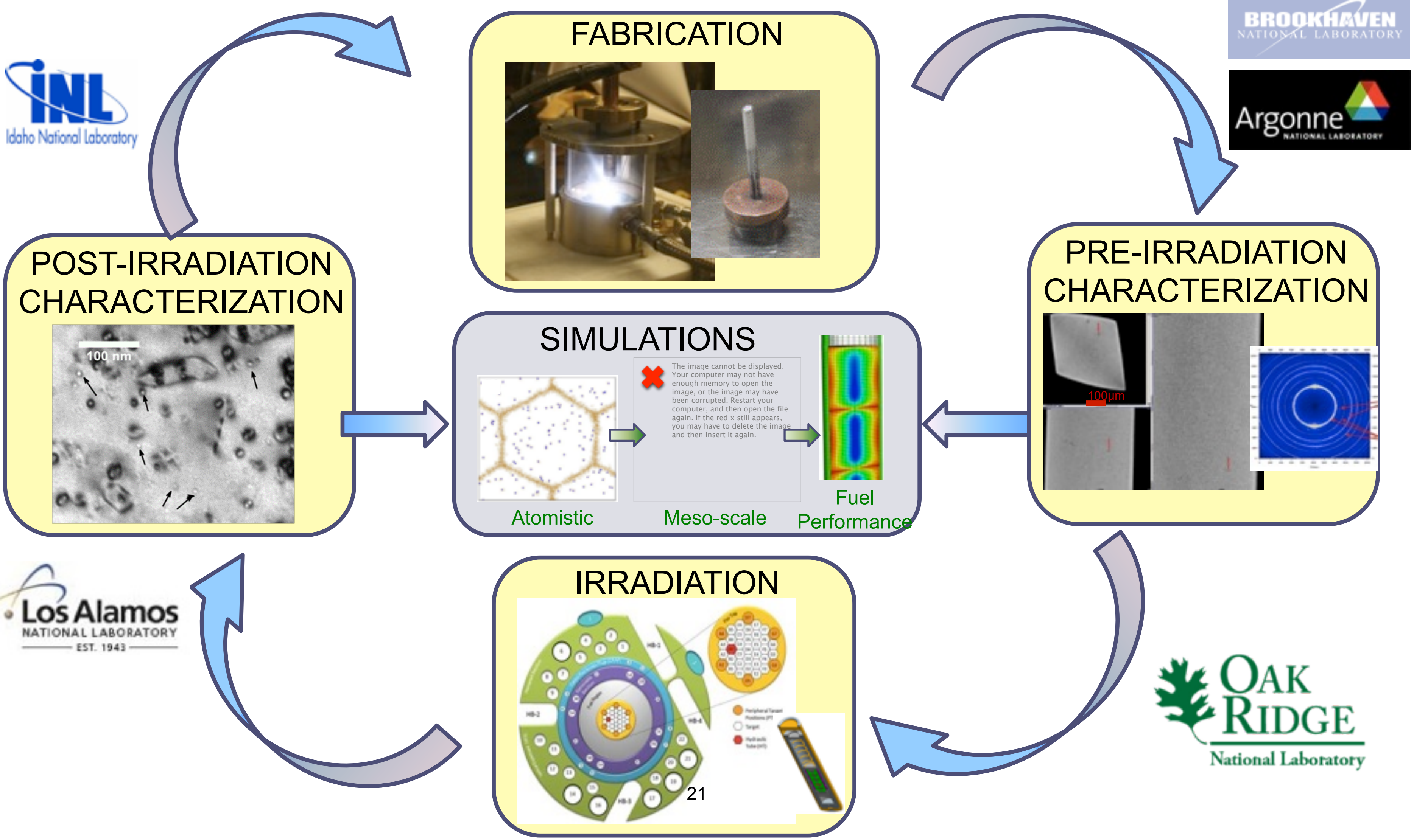
Connecting Experiments and Simulations: “Science-Based Approach”

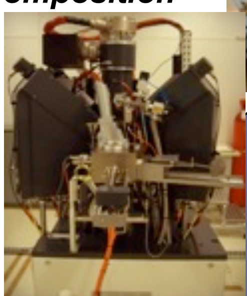


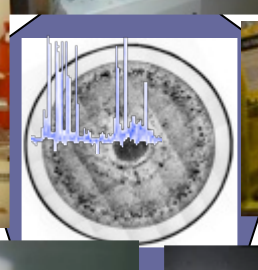
Laser-based Technique Development and Integrated PIE Instrumentation

- **Integrated Instrument Measurement System: develop technique and equipment to measure and observe same position (fiducial marking) on identical sample on multiple instruments at high spatial resolution (SEM, EPMA, STDM, μ-XRD, MPM, TCM, …)**

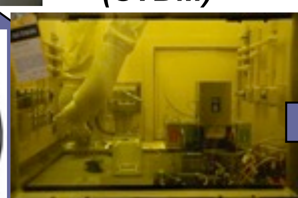
Electron Probe MicroAnalyzer (EPMA) – chemical composition

Scanning Electron Microscope (SEM) - microstructure





Scanning Thermal Diffusivity Microscope (STDM)



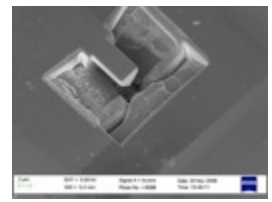
Micro-focus X-ray Diffractometer (μ-XRD) – crystal phase

Mechanical Properties Microscope (MPM) - mechanical

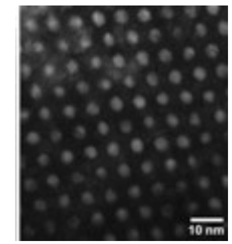
Higher resolution studies

Next Gen

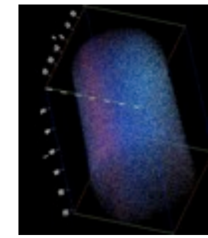
- **Highest spatial resolution studies on particular features utilizing FID sample preparation include TEM, FEG-STEM, APT, micro- & nano-indentation, DOE light sources, etc.**



FIB/ nano-indent

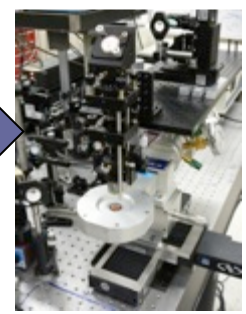


TEM



Atom Probe Tomography (APT)

Micron level spatial resolution: thermal effusivity, thermal diffusivity, and thermal conductivity values compare very well with those known from the literature



Thermal Conductivity Microscope (TCM)

	Sample A (SiO_2)	Sample B (CaF_2)
Phase lag (deg)	60.4	46.3
Effusivity ($J/m^2 s^{1/2} K$), measured	1490	4570
Effusivity ($J/m^2 s^{1/2} K$), literature	1436	4989
Effusivity error	<4%	~8%
Diffusivity (m^2/s) measured	9.80×10^{-7}	3.25×10^{-6}
Diffusivity (m^2/s) literature	9.5×10^{-7}	3.4×10^{-6}
Diffusivity error	3%	4%
Conductivity (W/m K), measured	1.47	8.24
Conductivity (W/m K), literature	1.4	9.2
Conductivity error	5%	10%
Effusivity ($J/m^2 s^{1/2} K$), measured including $R_{th} = 5 \times 10^{-9} m^2 K/W$	1460	4180

	Isotropic Ingot	Anisotropic rolled foil	Percent change
Young's Modulus (Gpa)	102	71	30
Shear Modulus	36	25	30

MPM taken into mock-up. First type measurements on U-Mo alloy and textured U-Mo material.